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Recent Progress in HTS Bulk Technology and Performance at NSC

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Abstract

This paper describes the current status of large single-grained RE-Ba-Cu-O (where RE: Y or rare earth elements) bulk superconductors with excellent superconducting properties in Nippon Steel Corporation. Intensive research on RE-Ba-Cu-O revealed that the optimal RE element is different for application requirements. While Gd-Ba-Cu-O bulk superconductors are greatly attractive for almost all bulk applications, Eu-Ba-Cu-O is suitable for compact NMR/MRI and Dy-Ba-Cu-O for current leads. In addition, single-domain bulk superconductors have been grown up to 150 mm in diameter by incorporating the RE compositional gradient method. Furthermore, progress of machining technology enables to obtain various complicated shapes of bulk superconductors

Keywords: Bulk superconductors, RE-Ba-Cu-O, Gd-Ba-Cu-O, Trapped magnetic fields, Current leads

1. Introduction

High temperature superconducting (HTS) bulk materials of RE-Ba-Cu-O are highly attractive for practical applications because of their excellent and unique features: 1) large current transport capacity in the presence of strong magnetic fields, 2) automatically stable levitation without active control systems and 3) extremely high trapped field ability in compact space. In addition, HTS bulks require no metal substrates like HTS tapes, leading to the enhancement of the effective critical current density (J_c). Thus, various applications using HTS bulks can be expected, for examples, current leads, fault current limiters, flywheel energy storage systems, wind power generators, ship motors, compact NMR/MRI and so on. In order to realize these applications, large and excellent HTS bulks are required. Nippon Steel Corporation (NSC) succeeded in developing large-grained Y-Ba-Cu-O bulk superconductors with high J_c values by

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controlling the crystal growth and the microstructure for the first time in the world [1,2]. Since then, the research and development of HTS bulks has been making a steady progress. This paper describes the current status of large-grained RE-Ba-Cu-O bulks with excellent superconducting properties in NSC.

2. Recent progress in HTS bulk technology and performance

2.1. Gd-Ba-Cu-O bulk superconductors and the trapped field properties

LRE-Ba-Cu-O (LRE: light rare elements = Nd, Sm, Eu, Gd) is more promising because it can trap higher magnetic fields than Y-Ba-Cu-O. However, it is not easy to obtain a large and excellent crystal in LRE-Ba-Cu-O when it is melt-processed in air. In LRE-Ba-Cu-O, the RE/Ba substitution is promoted with increasing oxygen content, resulting in the deterioration of critical temperature (T_c). In order to suppress the RE/Ba substitution to an appropriate amount, the melt-processing in a reduced oxygen pressure is employed. From a commercial viewpoint, the process in air is more desirable. Although small samples of LRE-Ba-Cu-O melt-processed in air are reported, there are few reports on large crystals grown in air. This is mainly because it is difficult to remove the residual oxygen gas from the melted precursor in a large sample, compared with a small sample. As a result of the thorough investigation on LRE-Ba-Cu-O, we found that the careful control of heat treatment and the addition of Ag_2O enable to produce large crystals with high trapped fields in Ga-Ba-Cu-O, having the smallest ionic radius in LREs, even when they are melt-processed in air [3]. Fig.1 shows the trapped field distributions at 77 K : (a) Y-Ba-Cu-O and (b) Gd-Ba-Cu-O 60 mm in diameter and 20 mm in thickness. As shown in Fig.1, the trapped field of Gd-Ba-Cu-O is two times higher than that of Y-Ba-Cu-O. Therefore, Gd-Ba-Cu-O is highly attractive for compact and high magnetic field applications.

The trapped field ability of HTS bulks can be enhanced by cooling to lower temperatures. However, the electromagnetic force induced inside the sample is proportional to the trapped field and as a result the sample may fracture during high field activation. Although a trapped field of 17 T at 29 K was reported for between two small disks (26.5-mm-diameter) of Y-Ba-Cu-O [4], there are few reports on high trapped fields for one large crystal. This is primarily because the induced electromagnetic force increases with the sample size and partly because the sample uniformity may decrease with the sample size, leading to the deterioration of the mechanical properties. Fig.2 shows the temperature dependence of trapped field for one large crystal of Gd-Ba-Cu-O 46 mm in diameter reinforced by a stainless steel ring when a 10-T superconducting solenoid magnet is used for the applied field of the field cooling process. It is inferred from Fig.2 that Gd-Ba-Cu-O bulks have the potential of trapped fields greater than 10 T at around 40 K.

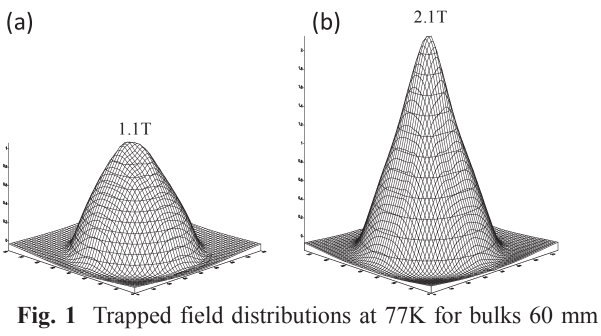

Fig. 1 Trapped field distributions at 77K for bulks 60 mm in diameter and 20 mm in thickness: (a) Y-Ba-Cu-O and (b) Gd-Ba-Cu-O.

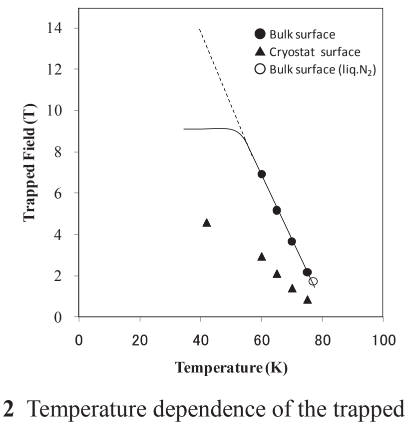

Fig. 2 Temperature dependence of the trapped field for a Gd-Ba-Cu-O bulk 46 mm in diameter.

2.2. Optimizing the RE elements for some specific applications

Intensive research on RE-Ba-Cu-O revealed that the optimal RE element is different for application requirements. Although Gd-Ba-Cu-O is greatly attractive for almost all bulk applications, it is not necessarily the most appropriate for some specific applications. For example, it is expected that a small and easy-to-use NMR/MRI spectrometer can be assembled using HTS bulks. NMR/MRI application requires extremely homogeneous magnetic fields. By using Gd-Ba-Cu-O, ^{1}H NMR signal less than 800 Hz signal width at 4.7 T (200 MHz) was observed [5]. However, it is difficult to achieve further homogeneous fields as long as Gd-Ba-Cu-O is used, because Gd ion has a comparatively large paramagnetic moment, resulting in reducing the uniformity of trapped fields. For the further improvement of field homogeneity, it is necessary to select RE elements with a smaller paramagnetic moment such as Y, Sm and Eu. Among them, Eu-Ba-Cu-O is found to be the optimal composite from the view point of both trapped field properties and productivity. The fabrication technology of Gd-Ba-Cu-O is applicable to Eu-Ba-Cu-O, but much more careful control of the crystal growth is required for Eu-Ba-Cu-O.

Next, let us consider another application. A compact and superior-field-tolerant current leads can be expected by utilizing RE-Ba-Cu-O bulks, because they have a more excellent J_c-B properties than other types of HTS materials. Current lead application requires a low heat leak, which means a low thermal conductivity of the components. The thermal conductivity of HTS materials is two orders of magnitude smaller than that of copper, a conventional current lead material. Fujishiro et al. investigated the thermal properties of various RE-Ba-Cu-O and found that Dy-Ba-Cu-O has a lower thermal conductivity than other RE-Ba-Cu-O such as RE=Y, Gd [6]. Therefore, Dy-Ba-Cu-O is an ideal material for current leads. However, since the RE-Ba-Cu-O compounds are brittle ceramics, they might fracture during handling without reinforcement. Fig.3 displays the appearance of Dy-Ba-Cu-O bulk current leads. As shown in Fig.3, the bulk sits in a rigid fibergrass housing to create a robust and reliable lead, and the both ends of the bulk are each soldered to a copper electrode for easy handling and connections.

2.3. Large single-grained HTS bulk superconductors 150 mm in diameter

The requirement for larger single-grained HTS bulks is increasing, in accordance with the advance of application development. This is mainly because a large crystal leads to the enhancement of application performance: the levitation force in bearing applications or the total flux density in magnetic applications is approximately proportional to the size of a single-grained superconductor. However, during the growth process of a large crystal, the super-cooling temperature, ΔT, becomes too large at the edge of the melted precursor and the large ΔT causes undesirable nucleation at the position apart from the seed. As a result, it

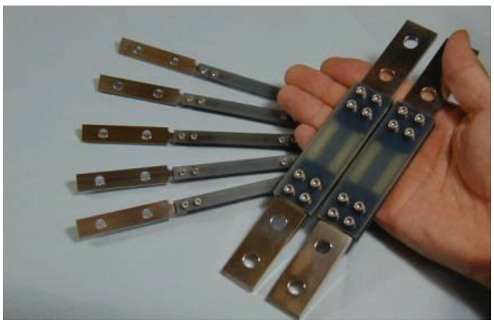

Fig. 3 Appearance of Dy-Ba-Cu-O bulk current leads.

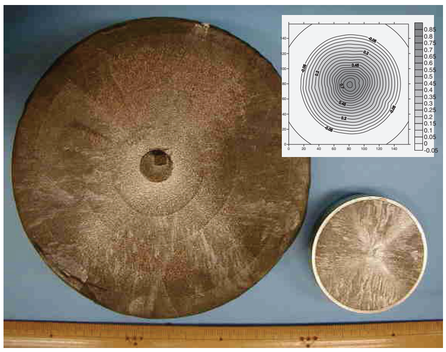

Fig. 4 Top view of a Gd-Ba-Cu-O 150 mm in dia. (left side) and a 60 mm-sample (right side).

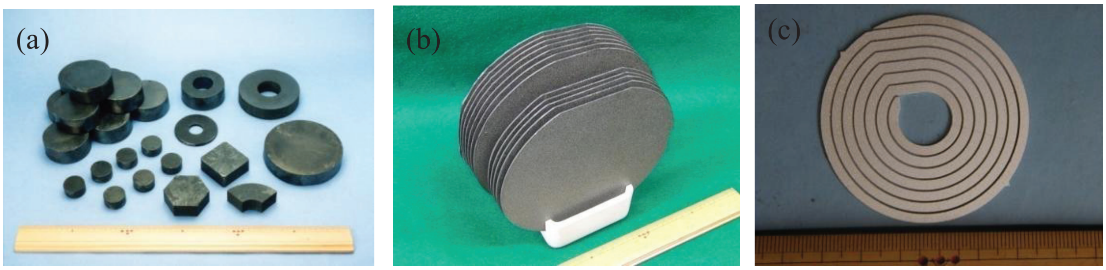

Fig. 5 Examples of machined bulks: (a) various shapes, (b) thin-sliced disks and (c) a coil-shaped sample.

is significantly difficult to produce a single crystal larger than 100 mm in diameter. This problem can be overcome by incorporating the RE compositional gradient in the basic melt-processing of RE-Ba-Cu-O [7]. In other words, the ΔT can be decreased by employing the RE compositional gradient in the radial direction concentrically, since different RE elements have a different melting temperature. For example, the content of Gd in the center portion is set at 100 % and the mixed rate of another RE element with a lower melting temperature than Gd such as Dy increases by several % from layer to layer towards to the periphery. Fig.4 shows an appearance of a single-grain 150 mm in diameter of Gd-Ba-Cu-O with a compositional gradient of Dy. The insert in Fig.4 is the trapped field distribution at 87 K, indicating that the sample is a single crystal with no serious weak-links.

2.4. Progress in machining technology and various shapes of HTS bulk materials

Advance of machining technology enables us to obtain various complicated shapes of bulk superconductors. In bulk applications, as-grown crystals are not utilized as they are, and they are machined into various shapes depending on the application requirements, such as disks, rings, squares, hexagonal shapes and so on, as illustrated in Fig.5. Recently, more complicated shapes are available by machining, such as silicon-wafer-like disks 1 mm in thickness and a coil-shaped bulk [8]. It is expected that a great variety of shapes will expand the possibility of the bulk applications further and further.

3. Summary

In this paper, the recent progress in material technology and performance for large-grained RE-Ba-Cu-O bulk superconductors with strong pinning force is described. The research and development of HTS bulk materials has been making a steady progress, in accordance with the advance of application development. HTS bulks can be expected to create a new frontier field in superconducting applications.

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